Environmental Testing of MEMS for Space Applications

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Agenda

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Environmental Verification Objectives

The fundamental purposes of an environmental verification and test program:

- to qualify designs for launch and in-service conditions.
- to simulate the launch environment.
- to screen flight hardware for manufacturing workmanship defects.
- demonstrate the quality and reliability of a design.
- demonstrate its suitability for the intended purpose or mission.

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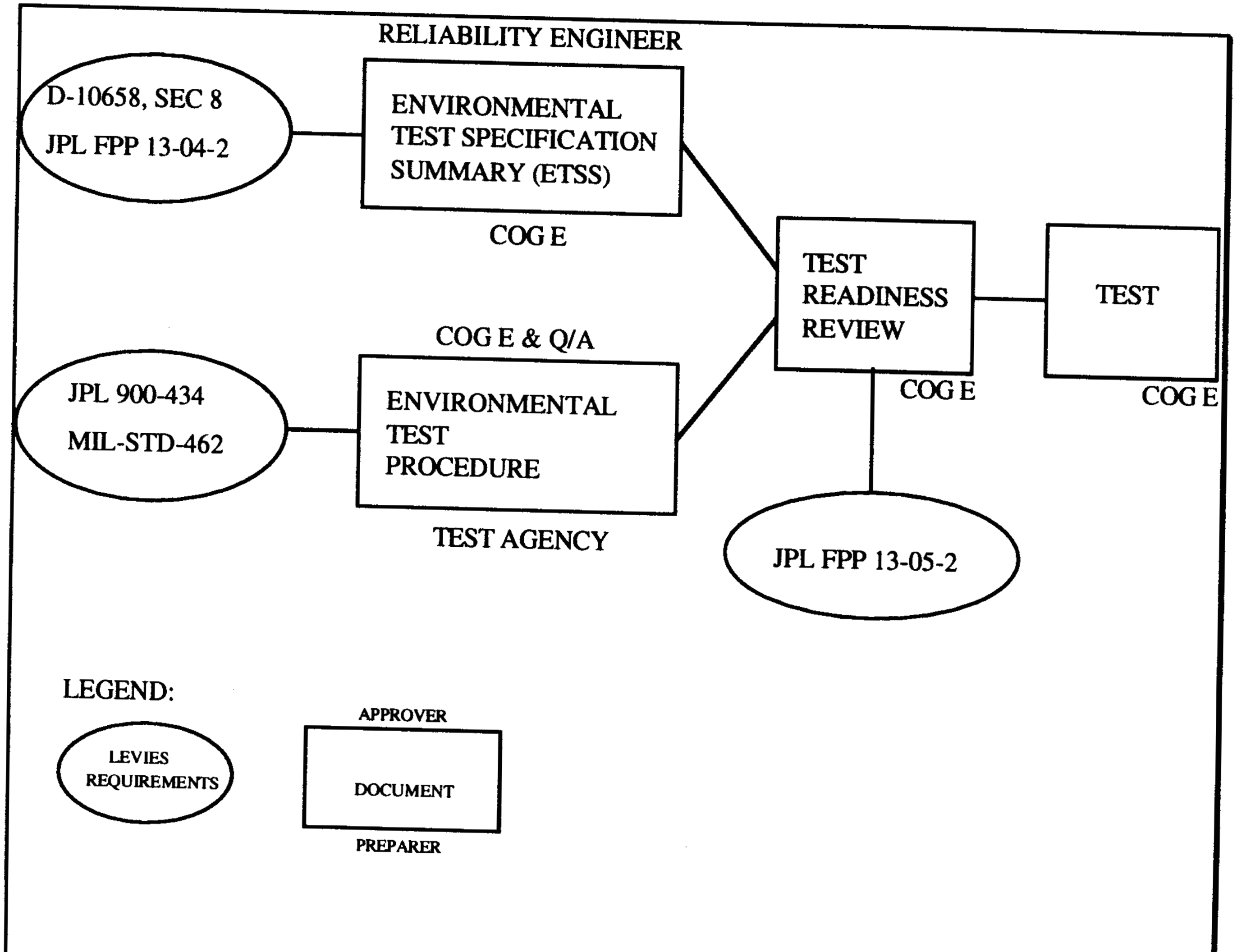
Test Sequencing

To accurately simulate the space environment sequence, flight hardware testing should be performed as follows:

1. Dynamic testing (in order as required)
   - sinusoidal vibration
   - transient vibration
   - pyroshock
   - acoustics
2. Thermal-vacuum testing
   - temperature dwell
   - temperature cycling

Space Environmental Test Program Process



TEST AUTHORIZATION FLOW

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A Typical Test and Analysis Configuration List

	Random Vibration	Acoustic	Pyro Shock	Thermal	VTMT	EMC	Mag. Mapping
Spacecraft	x	x	x	x		x	x
Propulsion Subsystem	x			x		x	
Main Engine Assembly	x			x			
Engine Gimbal Assy	x			x			
Gimbal Actuators	x		x	x			
Gimbal Drive Electronics	x		x	x	x	x	

This list can be as exhaustive or comprehensive as the program requires.

Environmental Design & Test Requirements

- Typical baseline space requirement depends on launch vehicle, spacecraft systems, etc.
- Launch Environment for both design and test (includes prelaunch operations, liftoff, and ascent) are as follows:
  - thermal conditions
  - deep space vacuum
  - insertion pressure decay
  - random and sinusoidal vibration
  - pyrotechnic shock
  - acoustic noise

Thermal

Spacecraft MEMS should operate over the following temperature ranges (whichever is more extreme):

- -55 °C to +70 °C

or

- ±20 °C of flight allowable

Definitions:

1. Operating Allowable Flight Temperatures - Temperature ranges when powered-on in a worst case operational mode (hot or cold).
2. Non-Operating Allowable Flight Temperatures - Temperature ranges when powered-off in a worst case non-operational mode (hot or cold). MEMS devices must be capable of returning to in-spec operation as temperatures return to Operating Allowable Flight levels.
3. Design Temperature Limits - Temperature limits for all functional and performance specifications.
4. Stabilization Temperature - A temperature at which the rate of change of its largest centrally located thermal mass is less than 2 °C per hour.
5. Control Temperature (Thermal/vacuum Conductive Heat Transfer Tests) - The temperature of the heat exchanger plate midway between input and output of heat exchange fluid.
6. Control Temperature (Thermal/vacuum Radiative Heat Transfer Tests) - The temperature of the major temperature control surface of the assembly (e.g. radiator).

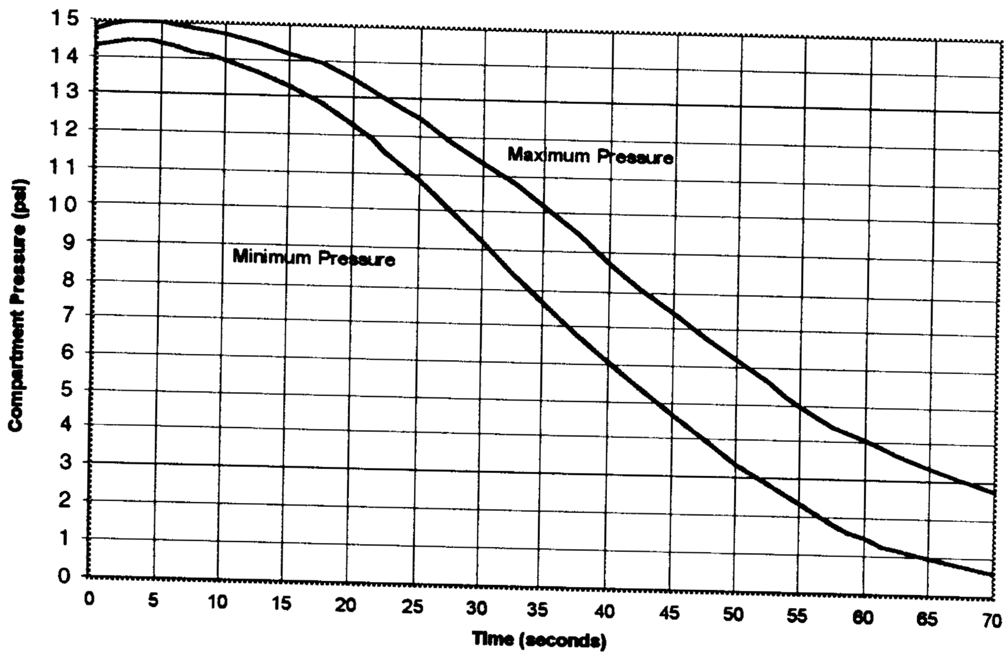
Thermal Radiation Levels

Allowable flight temperatures during the mission under exposure to the applicable worst case expected thermal radiation levels should not exceed the following:

Mission Phase	Direct Solar	Reflected Solar (Albedo)	Planetary IR (LW Radiation)
Earth Orbit:	0 to 1400 W/m^2 (5770K effective blackbody temperature)	0 to 0.32 0 to 450 W/m^2 (global annual mean) 0 to 0.70 W/m^2 (polar regions)	100 to 270 W/m^2 (206K to 262K effective blackbody temperature)
Deep Space Cruise: Near Earth	0 to 1400 W/m^2 (at earth perihelion)	Negligible beyond 4 earth radii	Negligible beyond 4 earth radii

Vacuum Pressure Decay

- The design pressure for a typical mission can be expected to decrease from 101325 N/m^2 (760 Torr) on Earth to 1.33×10^{-3} N/m^2 (1×10^{-5} Torr) in deep space.
- A typical launch pressure decay rate, showing launch vehicle internal fairing pressure versus time, is provided by the following:



Launch Pressure Decay Rate

- Assemblies affected by launch pressure decay should be designed with a recommended structural design factor of 1.0 on yield and 1.4 on ultimate if tested, or 1.6 on yield and 2.0 on ultimate if not.

Quasi-Static Accelerations

- Quasi-Static Accelerations are generated by rocket motor-induced forces and other external forces which change slowly with time and for which the elastic responses are relatively small.
- Typical assembly design requirements for quasi-static acceleration environments are provided by the following:

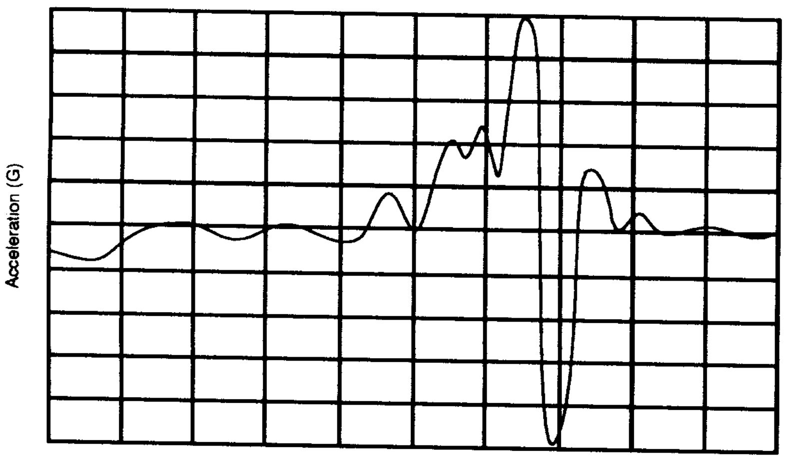
Axis	Acceleration (g)
Thrust	$+14 \pm 0.7$
Lateral	$+3 \pm 0.3$

- Qualification testing of MEMS for the quasi-static acceleration environment can be performed in a centrifuge.
- Or, a low frequency sine vibration test, conducted on an electrodynamic shaker, can often be substituted for the relatively expensive centrifuge trial.

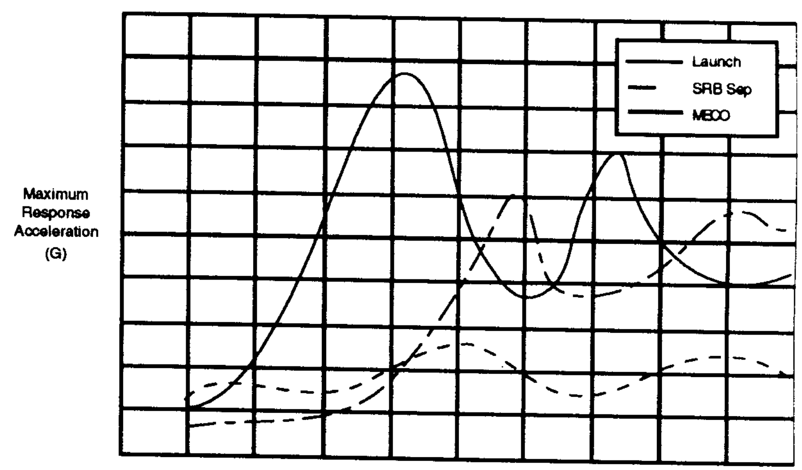
Sinusoidal Vibration

- Simulates the effects of significant flight environment launch transients, below ≈40 Hz.
- Sinusoidal vibration levels can be derived from the following example:

Step 1. Create analytically derived transient waveforms from various flight events:

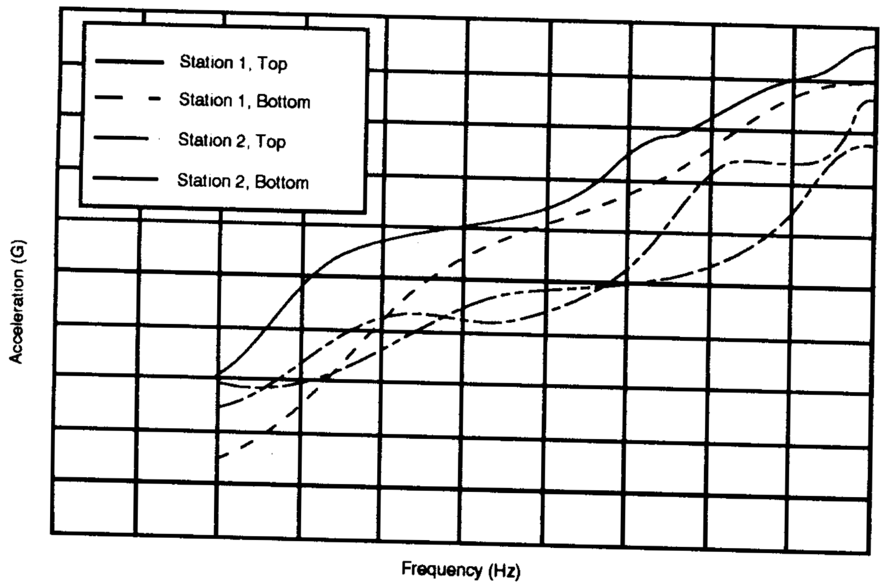


Step 2. Compute the shock spectra for each of the waveforms in Step 1:

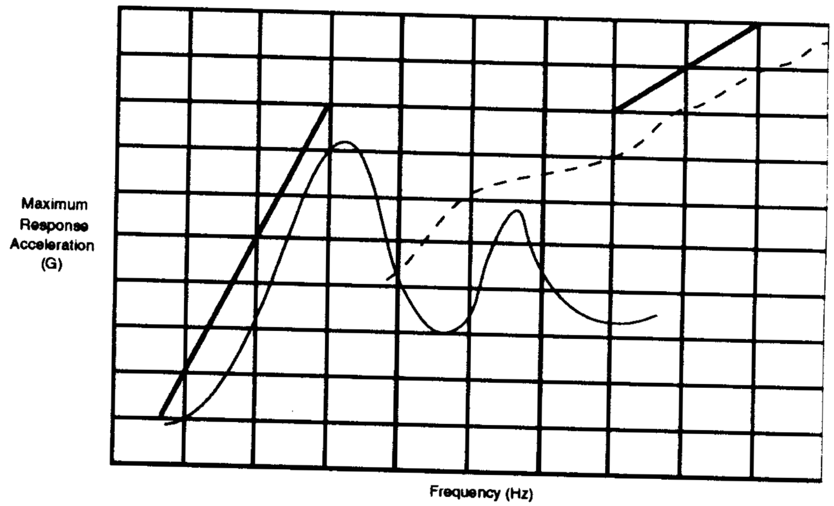


Sinusoidal Vibration (cont.)

Step 3. Take data from previous flight measurements:

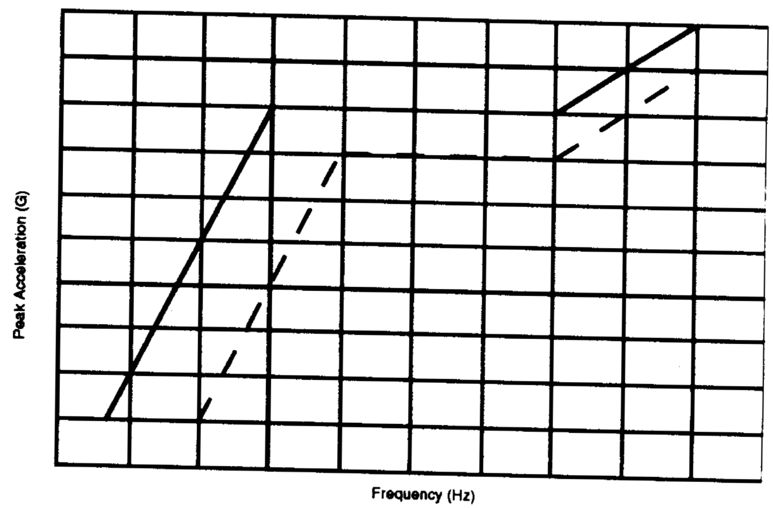


Step 4. Combine results from steps 2, and 3 and envelope:



Sinusoidal Vibration (cont.)

Step 5. Convert to a sine amplitude equivalent vs. Frequency by dividing shock response spectrum envelope in step 4 by q:



Space MEMS should be subjected to a set of swept sinusoidal vibration requirements similar to those shown below:

Spacecraft-Level		Assembly-Level	
Frequency (Hz)	**Level (Gs)**	**Frequency (Hz)**	**Level (Gs)**
5 - 10	1.0 cm DA**	5 - 20	1.9 cm DA*
10 - 100	2.0 (0 - peak)	20 - 100	12.0 (0 - peak)
100 - 200	1.0 (0 - peak)	100 - 200	3.0 (0 - peak)

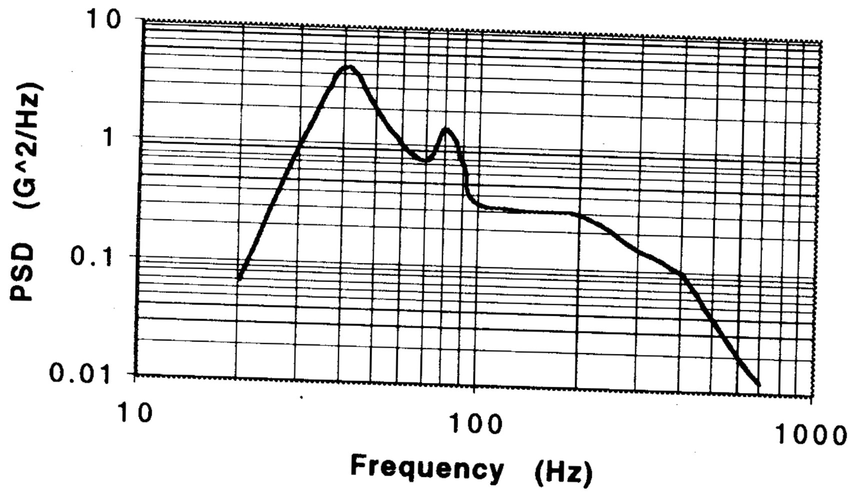
**DA: double amplitude displacement

Sweep rate: Qual: 1 octave per minute, once up or down in each of three orthogonal axes.
ProtoF test: 2 octaves per minute, once up or down in each of three orthogonal axes.
Acceptance: same as protoflight.

Random Vibration

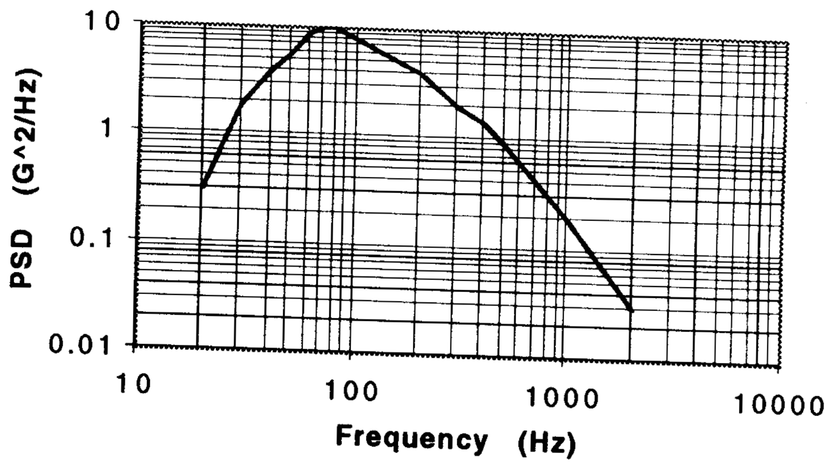
- It is caused primarily by acoustic noise in the payload fairing at launch, which is in turn induced by external aerodynamic forces due to dynamic pressure and reflection of rocket exhaust from the ground.
- Random vibration criteria should be developed by the process described in the following four steps:

1. Determine the Power Spectral Density (PSD).



Vibration levels transmitted to flight article through mounts

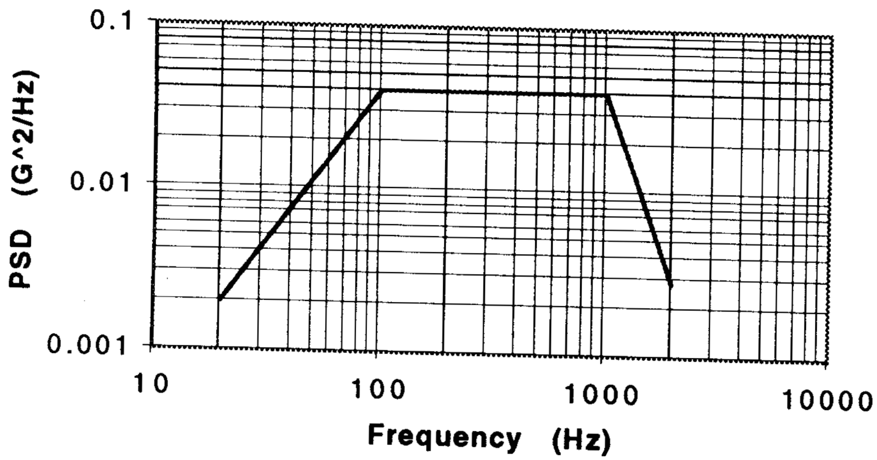
2. Perform an analysis to predict the payload/flight article's vibration response to the launch vibroacoustic environment.



Payload/flight article response to vibroacoustic environment

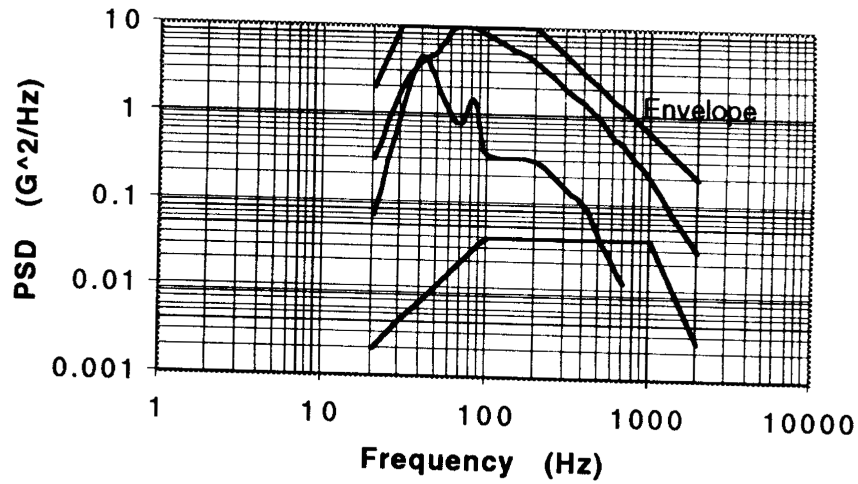
Random Vibration (cont.)

3. Establish a minimum level of vibration for workmanship screening.



Minimum vibration levels for workmanship defect detection

4. Envelope the curves from steps 1-3 to produce a composite random vibration specification for the test article, as illustrated below.



Composite random vibration envelope

Random Vibration Specifications

Recommended random vibration environments for both spacecraft and assembly-level testing are specified in the following table:

Spacecraft-Level		Assembly-Level	
Frequency (Hz)	**Level**	**Frequency** (Hz)	**Level**
20 - 45	+10 dB/octave	20 - 80	+6 dB/octave
45 - 600	0.06 g^2/Hz	80 - 1000	0.25 g^2/Hz
600 - 2000	6 dB/octave	1000 - 2000	-12 dB/octave
Overall	**7.7 grms**	**Overall**	**17.6 grms**

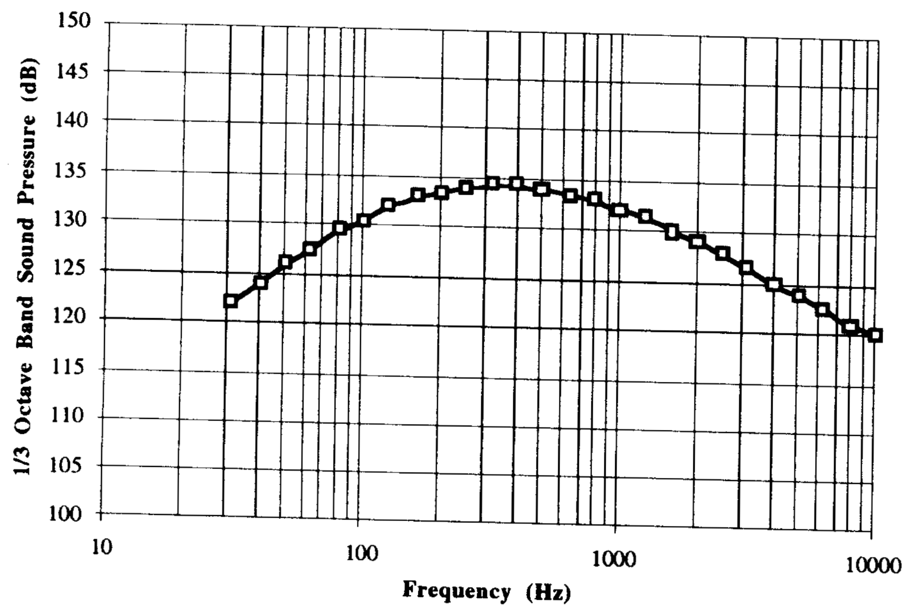
<u>Duration</u>:

Design: 3 minutes in each of 3 orthogonal axes
ProtoF test: 2 minutes in each of 3 orthogonal axes
Acceptance: same as protoflight

Acoustic noise

- Acoustic noise results from the propagation of sound pressure waves through air and other media.
- Acoustic noise is generated by:
  - release of high velocity engine exhaust gases during the launch of rocket,
  - the resonant motion of internal engine components,
  - the aerodynamic flow field associated with high speed vehicle movement through the atmosphere.
- Acoustic energy is the primary source of vibration input to a space launch vehicle.
- Acoustic energy gets transmitted to the mission payload in two ways:
  - the fluctuating pressures within the payload fairing impinge directly on exposed spacecraft surfaces, inducing vibration in high gain antennae, solar panels and other components having a large ratio of area-to-mass.
  - the fluctuating external pressure field causes an oscillatory response of the rocket structure, which is ultimately transmitted through the spacecraft attachment ring in the form of random vibration.

Typical Acoustic Specification

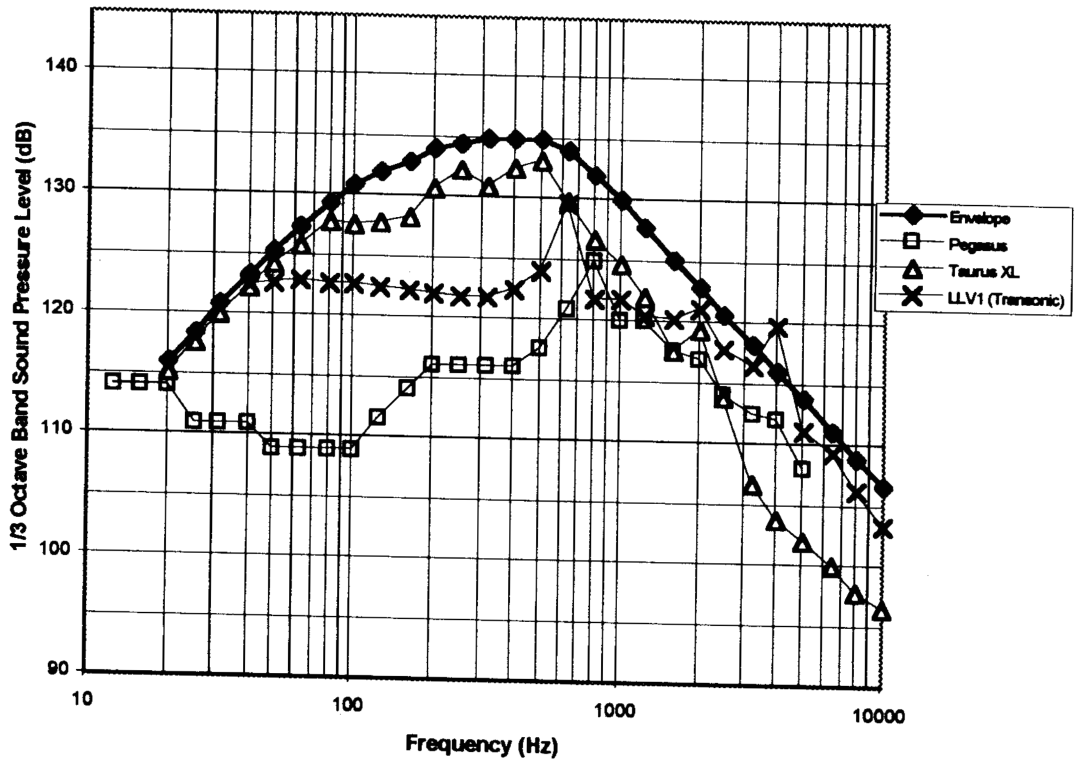


Typical Acoustic Noise Requirement

Calculation of Overall Sound Pressure Level (OASPL)

Center Frequency	SPL (dB)	Pressure P (Pa)	Squared Pressure
31.5	122.0	25.2	633.9
40.0	124.0	31.7	1004.6
50.0	126.0	39.9	1592.2
63.0	127.5	47.4	2249.1
80.0	129.5	59.7	3564.5
100.0	130.5	67.0	4487.5
125.0	132.0	79.6	6338.7
160.0	133.0	89.3	7979.9
200.0	133.5	94.6	8953.6
250.0	134.0	100.2	10046.2
315.0	134.5	106.2	11272.0
400.0	134.5	106.2	11272.0
500.0	134.0	100.2	10046.2
630.0	133.5	94.6	8953.6
800.0	133.0	89.3	7979.9
1000.0	132.0	79.6	6338.7
1250.0	131.5	75.2	5649.4
1600.0	130.0	63.2	3999.4
2000.0	129.0	56.4	3176.9
2500.0	128.0	50.2	2523.5
3150.0	126.5	42.3	1786.5
4000.0	125.0	35.6	1264.7
5000.0	124.0	31.7	1004.6
6300.0	122.5	26.7	711.2
8000.0	121.0	22.4	503.5
10000.0	120.0	20.0	399.9
		RSS Pressure = 351.8 Pa	
		20 log(351.8/2E-5) = 144.9 dB	

Acoustic Noise Envelope Encompassing Three Launch Vehicles



Envelope of Acoustic Flight Data

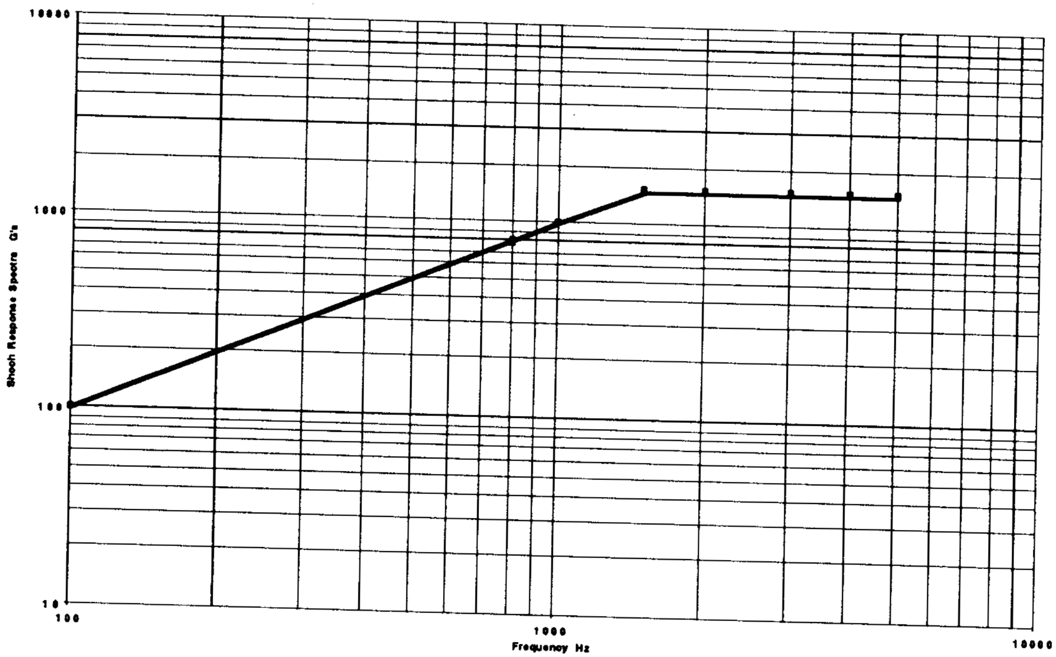
At the subsystem level, acoustic testing is generally not conducted for space MEMS due to their low ratio of area-to-mass.

Typical Acoustic Noise Test Levels

Frequency (Hz)	F.A. SPL (dB ref 20 μPa)	Qual SPL (dB ref 20 μPa)	Tolerance (dB)
31.5	129.0	132.0	+6, -3
40	131.0	134.0	+5, -3
50	132.5	135.5	+5, -3
63	134.0	137.0	+5, -3
80	135.0	138.0	+4, -3
100	135.5	138.5	±3
125	136.0	139.0	±3
160	136.0	139.0	±3
200	135.5	138.5	±3
250	135.3	138.3	±3
315	135.0	138.0	±3
400	134.0	137.0	±3
500	132.0	135.0	±3
630	130.5	133.5	±3
800	129.0	132.0	±3
1000	126.5	129.5	±3
1250	125.0	128.0	±3
1600	123.0	126.0	±3
2000	121.0	124.0	±3
2500	119.0	122.0	±3
3200	117.0	120.0	±3
4000	115.0	118.0	±3
5000	113.0	116.0	±3
6400	111.0	114.0	±3
8000	109.0	112.0	±3
10000	107.0	110.0	±3
OASPL	*145.8*	*148.8*	*±1*

Pyrotechnic Shock

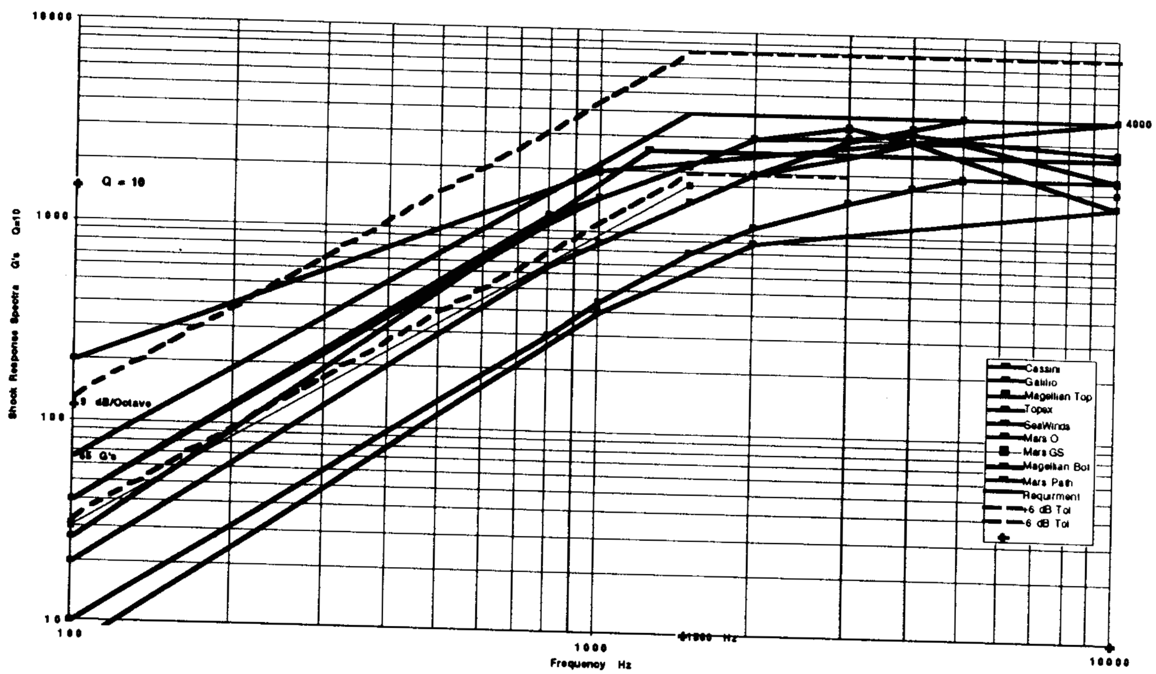
- Pyrotechnic Shock is associated with the firing of an explosive device.
- A typical pyrotechnic shock requirement is illustrated in the figure below::



Typical Pyrotechnic Shock Requirement

Another Possible Pyrotechnic Shock Environment Requirement

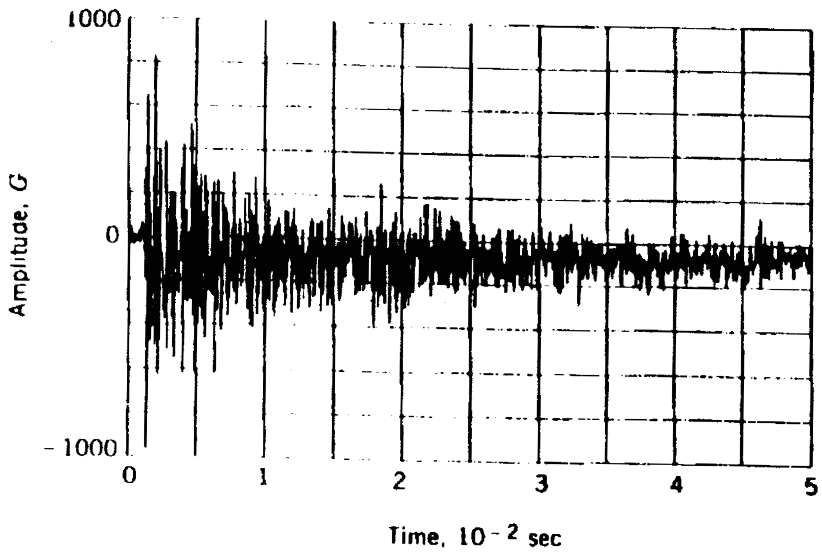
- The shock input is applied at the assembly mounting points in each of 3 orthogonal axes.
- This spectrum represents a 2σ environmental level, intended to encompass 95% of all expected shock environments for all available launch vehicles.



Subassembly Pyrotechnic Shock Design Requirement

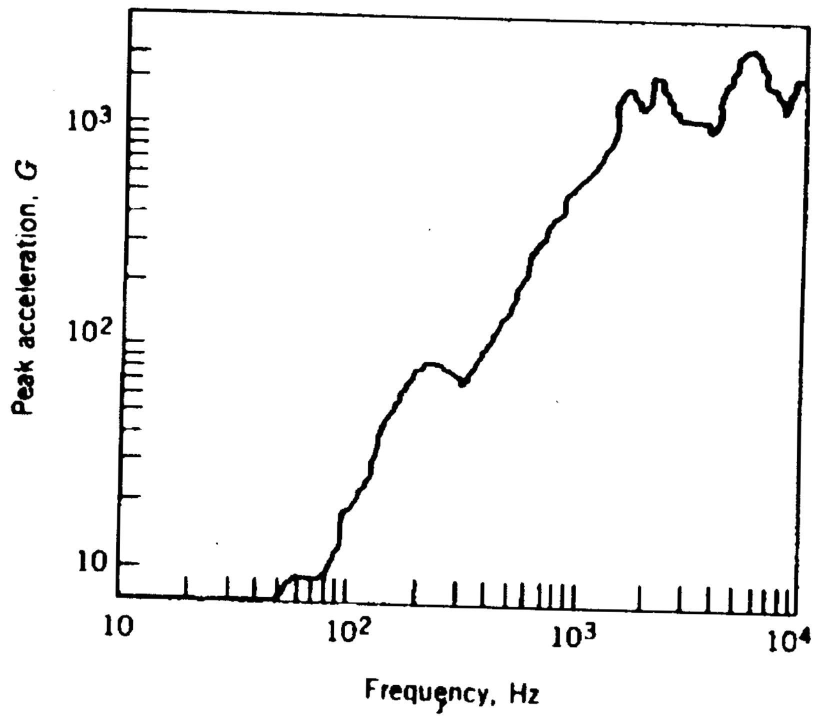
Actual Pyrotechnic Shock Spectrum

The figure below illustrates a typical acceleration versus time trace from an actual pyrotechnic shock actual pyrotechnic shock event.



Pyro Shock Acceleration Time History

The figure below illustrates a typical measurement of the frequency-domain response



Frequency Response to Pyro Shock

Recommended Shock Test

MEMS should be tested to the shock spectrum (Q=10) as shown below:

FREQUENCY (Hz)	ACCEPTANCE (G PK)	PROTOFLIGHT (G PK)
100	40	60
100-1500	9.2 dB per Octave	9.2 dB per Octave
10000	2500	3750

Shock Response Spectrum (Q=10)